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THE "TAVISTOCK" TRANSIT THEODOLITE

BY E. WILFRED TAYLOR

(Messrs Cooke, Troughton and Simms, Ltd.)

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ABSTRACT. A Conference of Surveyors was held at Tavistock in 1926 and a specification for a service pattern Theodolite was there drawn up. The "Tavistock" theodolite, a description of which follows, was designed to this specification and incorporates a novel method of reading the circles.

INTRODUCTION

A CONFERENCE was convened at Tavistock in 1926 at which high officials of the Hydrographic Department of the Admiralty, the Geographical Section of the War Office, the Theodolite Sub-Committee of the R.E. Board, the Ordnance Survey and the Colonial Survey Committee, met representatives of the leading British firms specialising in the manufacture of surveying instruments. The object of the Conference was to draw up a specification for a theodolite which would be suitable for general service requirements.

The "Tavistock" theodolite was designed to meet the requirements of the services and also for use as a precise general purpose instrument, suitable for all but first-order work in the field.

Figs. 1 and 2 illustrate the general appearance of the instrument and the keyed references will make clear the various parts.

NOMENCLATURE (Figs. 1 and 2)

A. Cover-plate enclosing optical system whereby horizontal circle is read.
B. Box enclosing optical system whereby vertical circle is read.
C. Horizontal circle (not shown).
D. Vertical circle.
E. Eyepiece for reading vertical circle.
E'. Milled head for setting vertical circle micrometer.

F. Eyepiece for reading horizontal circle.
F'. Milled head for setting horizontal circle micrometer.
G. Object glass.
H. Focussing head for telescope.
H'. Screw focussing eyepiece.
J. Cover to adjusting screws for graticule.
K. Plate spirit level.
L,L'. Screwed caps allowing access to adjustments.
M. Altitude spirit level.
M'. Prism reader for altitude spirit level.
N. Zero-setting adjustment for vertical circle.
O. Tribrach.
P. Footscrews.
Q. Connection for leads from battery.
R. Clamp for lower plate.
R'. Slow-motion screw for lower plate.
S. Clamp for upper plate.
S'. Slow-motion screw for upper plate.
T. Clamp for telescope.
T'. Slow-motion screw for telescope.
U. Setting screw for altitude spirit level.
V. Reflector for illuminating vertical circle.
V'. Electric illumination for vertical circle.
W. Reflector for illuminating horizontal circle.
W'. Electric illumination for horizontal circle.
X. Bright field illumination to telescope.
Y. Trivet stage.
Z. Seating for magnetic compass.

Specification

Circles. Horizontal—divided on glass. Figured 0° to 360° clockwise.

Vertical—divided on glass. Figured 0° to 180°, 0° to 180° anti-clockwise. With circle left and telescope horizontal, zero is at the zenith.

Both circles are read by a special micrometer reading device direct to one second of arc.

Axes. The Horizontal circle is carried on an independent axis to allow the instrument to be used for repetition or reiteration.

Slow Motions. A differential slow-motion screw (not shown in the figures) is fitted to the upper plate and to the vertical circle, and provides a coarse and fine adjustment. One turn of the coarse movement knurled head moves the telescope through about 30 minutes and one turn of the fine movement knurled head moves it through about 5 minutes. Very accurate pointing in azimuth and altitude is thus rendered possible.

Telescope. "Anallatic" type of 1·5 in. aperture. Focussing is internal and operated by a knurled head mounted at the end of the transit axis. The telescope transits at both ends and the axis is supported in complete round screwed-down bearings.

The eyepiece is of the screw focussing inverting type giving a magnification of 25. Open sights are fitted to both sides of the telescope.

Graticule. Cross lines on glass with the addition of 1 in 100 stadia lines. The graticule may be interchanged without disturbing the collimation of the telescope.

Spirit Levels. Plate—40 seconds per 2 mm. run.

Altitude—20 seconds per 2 mm. run. A prism reader allows the setting to be observed from the eye-end of the telescope in both vertical circle positions. The altitude level is set by means of a fine screw either before or after the pointing of the telescope.

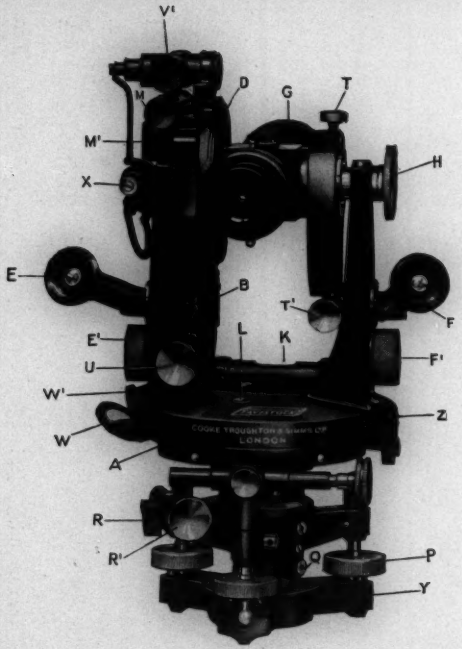


Fig. 1.

"Tavistock" transit theodolite.

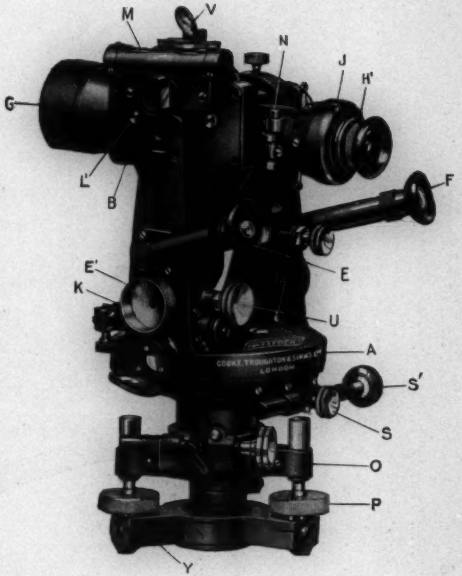


Fig. 2.

Tribrach. Three ball-headed levelling screws with dust covers to the threaded portions.

Tripod. Open frame legs with self-adjusting fittings to the hinge pins. A circular bubble is fitted to the tripod head for rough levelling and a centering movement of 1·5 inches is provided. The thread for engaging the instrument is protected by a metal cap.

Illumination. The glass circles are arranged for illumination by daylight or by standard 4 volt lamps. In the former case adjustable reflectors pick up the light from some bright object, such as a white cloud. For night use the circles, altitude spirit level and telescope graticule are electrically illuminated and the lamps are easily accessible for replacement. The battery, rheostat and switch are attached to the tripod and connection is by plug and socket.

Case. The instrument complete with spares and accessories is packed in a metal (duralumin) case (Fig. 3). The latter is canvas covered and fitted with web carrying straps.

Weight. Instrument only: 11·75 lb.
Case, complete with accessories, tools and spares: 10·5 lb.
Tripod: 11 lb.

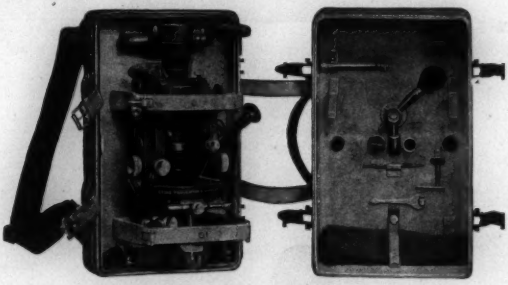


Fig. 3. Theodolite in metal box.

The Optical System (Figs. 4 and 5)

Light from the sky or a bright cloud is reflected into the instrument by the adjustable mirror *A* and half the beam passes through each of two double reflecting prisms *B* into the prisms *C*, where it is reflected downwards by the sloping faces *D* through the apertures *E* in the prism box into the glass circle *F*. This illuminating beam is slightly deflected before entering the prisms *C* and after reflection at the silvered surface of the glass circle receives a second reflection at the surfaces *D* and passes on to the surfaces *G* and thence into the reflecting prisms *H*. The two beams then proceed along parallel paths into the field prisms *J* where they are first directed towards each other and finally emerge united and at right angles to the plane of the diagram.

To an eye placed to receive the emergent beam the two openings *E* will appear to be illuminated by light reflected from the mirror *A*, and if the glass circle is graduated and figured on the surface *F* the lines and figures will be seen as dark marks against an illuminated background.

On introducing objectives *K* of suitable power in the positions indicated an

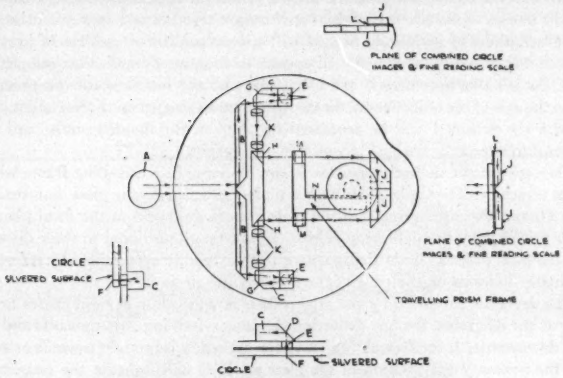


Fig. 4. Diagram of optical system for horizontal circle.

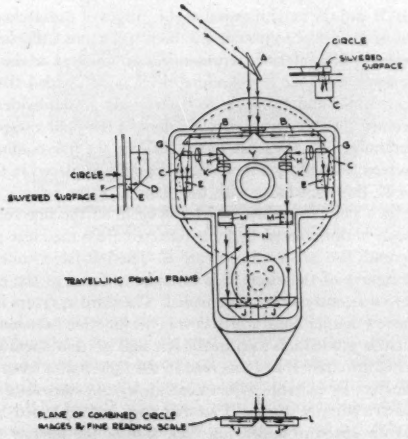


Fig. 5. Diagram of optical system for vertical circle.

image of the circle lines and figures appearing within the apertures *E* will be thrown into the focal plane *L* of the prisms *J*, and the optical parts are so disposed that the images of the two sets of lines are brought together and appear continuous. The graduations of both scale images will appear parallel to the line of junction between the prisms *J* and each will appear to increase numerically from left to right. As the two apertures *E* are 180° apart and the surface *L* of the prisms *J* lies on the axis of the objectives *K* the two graduations imaged on the line of junction between the prisms *J* will be separated by 180° on the divided circle, and this relationship is exactly attained by suitable adjustment.

Two achromatic deflecting prisms *M* are mounted in a travelling frame which carries a rack *N*. The latter gears with a pinion attached to the glass fine-reading circle *O*, and the displacement of the scale images produced in the focal plane *L* of the prisms *J* by the deflecting prisms *M* will be proportional to their distance from the focal plane *L*. This displacement may be readily determined by reference to suitable divisions on the edge of the fine-reading circle *O*.

The deviation produced by the prisms *M* is in a direction at right angles to the plane of the diagrams, the one deflecting the image-forming rays upwards and the other downwards. If the frame *N* carrying the prisms *M* is brought towards or away from the prisms *J* the rotation of the glass circle *O* will indicate the magnitude of the movement and the two sets of images in the focal plane *L* will move as one, either to the right or the left.

The total range of movement of the prisms *M* is one inch and the glass circle *F* is divided into intervals of 20 minutes. It is necessary to adjust the power of the deflecting prisms *M* and the magnification of the images of the circle graduations so that a movement of the former through one inch will cause a displacement of the latter through exactly one interval, representing 20 minutes at the centre of the circle. If at the same time the fine-reading circle is so divided that it records a movement of 20 minutes and the scale so determined is subdivided equally into minutes and seconds, then the exact displacement of the scale images in the focal plane may be determined by reference to the scale on the fine-reading circle *O*.

An opaque screen (Fig. 6) with three clear openings is placed in the focal plane of the objectives *K*, this coinciding with the plane *L* of the prisms *J*. The square opening (2) carries a pointer against which the scale on the fine-reading circle is read, and this scale is illuminated by light reflected from the clear portion of the glass circle *F* beneath the left-hand aperture *E*. The left-hand scale image of the graduations and figures of the circle *F* is brought to focus in the coarse-reading aperture (1) where a second pointer is provided. The third aperture is divided into two parts by a narrow opaque band which covers the junction between the prisms *J*. The image of a circle graduation seen in the left half of this opening is from one end of a diameter of the circle *F* and that seen in the right half is from the other end of the same diameter; by suitable adjustment under the control of the observer, these two images are slightly displaced so that they are separated by an interval that allows a narrow space to appear on each side of the narrow opaque band, which will be referred to as the "datum mark."

If the fine-reading circle is set to zero as in Fig. 6 *A* and the glass circle *F* is rotated relatively to the optical system a position of symmetry can be found when the images of the two diametrically opposite graduations of the circle *F* are equally disposed about the datum mark. If everything is in correct adjustment and the fine-reading circle *O* is then rotated to read 20 minutes 0 seconds, a second position of symmetry will be found when the images of the next two diametrically opposite graduations will be evenly disposed about the datum mark.

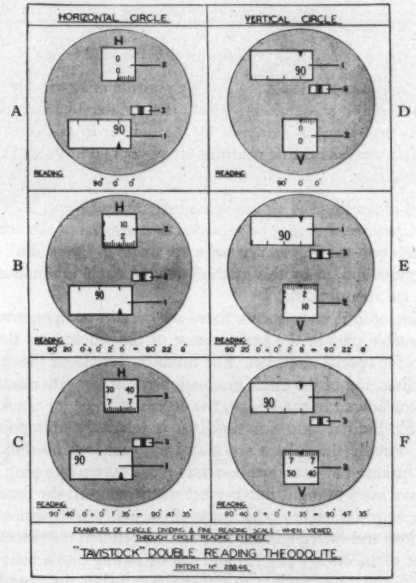


Fig. 6.

The method of recording the position of the glass circle *F* relatively to the optical system by which the circle is read will now be clear. In the first place the micrometer head must always be rotated until a position of symmetry is obtained (and, except in the special case when the readings are 0 and 20 minutes, only one such position will be found). The eye is then directed to opening (1), in which the image of a circle graduation will be seen opposite the pointer; this is the graduation short of the required reading and is, let us say, 90° 20′ as in Fig. 6 *B*. The eye is next

directed to the opening (2) and the fine reading is noted against the appropriate pointer, in this case 02′ 08″. The fine reading is always additive and never more than 20′, so that the complete reading is 90° 22′ 08″. If the circle *F* is rotated relatively to the reading system the angle through which it is rotated is easily determined if a position of symmetry is once more obtained in aperture (3) and the reading taken. The difference between the first and last readings will of course determine the angle through which the circle *F* was rotated, and it should be noted that as both ends of a circle diameter are involved the reading is always a mean of two graduations. Eccentricity of the circle *F* does not influence the numerical value of the readings.

To sum up, the procedure by which the circle is read is as follows:

> Set the micrometer, i.e. bring about a position of symmetry in aperture (3). Read the circle graduation opposite the pointer in aperture (1), and add the minutes and seconds indicated by the pointer in aperture (2). It will be seen that the coarse and fine readings are always additive and that estimation is never necessary.

The method of reading the circles is the invention of Capt. T. Y. Baker, R.N., and Mr R. W. Cheshire, and may be regarded as a reversal of the usual micrometer practice in which two moving spider webs are made to "straddle" symmetrically a fixed circle graduation, as by this method moving circle graduations are made to "straddle" a fixed datum mark.

In all precise optical instruments there are certain components which play a specially responsible part in the performance of the whole, and the mounting of such parts calls for special attention. For instance, certain of the optical elements involved in the imaging of the circle graduations must not move and this has been very carefully considered in the design, the degree of freedom of each prism being as far as possible limited to a direction that is relatively unimportant from this point of view. Finally the prisms are sealed in place and no difficulty has been experienced in making the instruments stand up to a severe bumping test. Once the scale images have been brought into correct relationship in the focal plane *L* they may, of course, be re-imaged to other parts of the instrument without the need for special precautions and each circle has its own independent micrometer and reading eyepiece. These eyepieces are pivoted and can be swung into a convenient reading position (Figs. 7 and 8) accessible to an observer using the theodolite in either a "circle left" or "circle right" position. Milled heads for operating the circle micrometers are mounted on the standards immediately below their corresponding eyepieces.

It will be clear from the preceding description that the two optical systems whereby the circles are read are quite independent. Access to the prism boxes is easily gained and Figs. 9 and 10 (which should be examined in relation to Figs. 4 and 5) show the optical systems as they appear on removal of the prism-box covers.

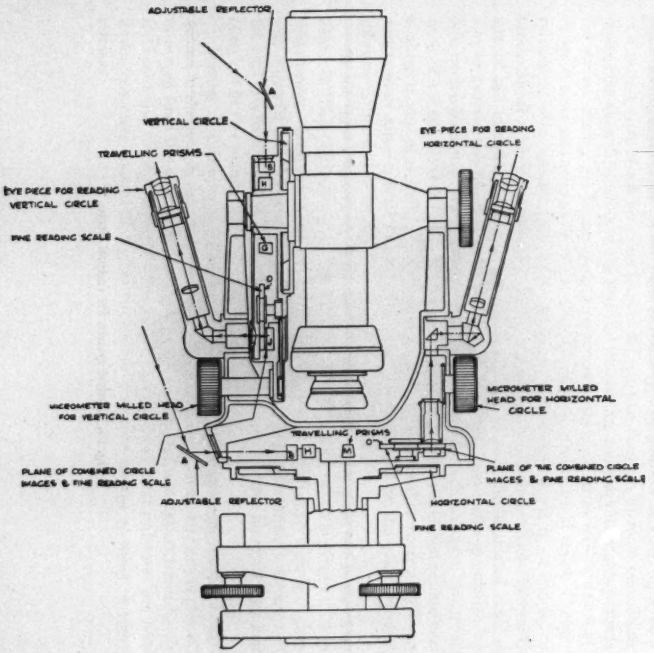


Fig. 7. Part section.

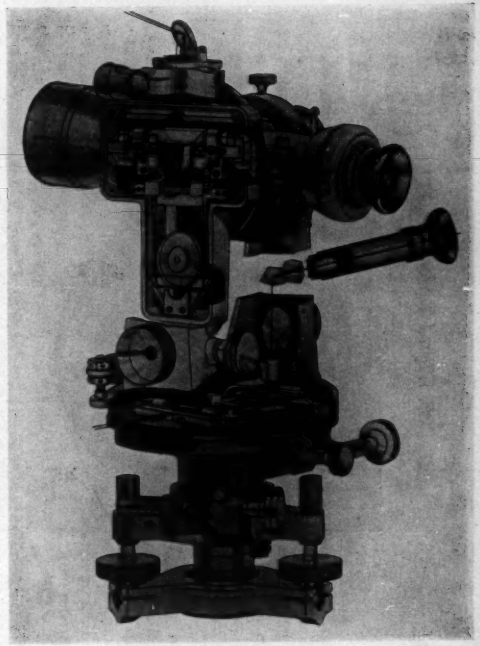


Fig. 8. Perspective view.

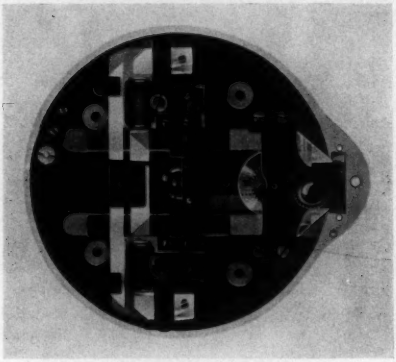


Fig. 9. Optical system for horizontal circle.

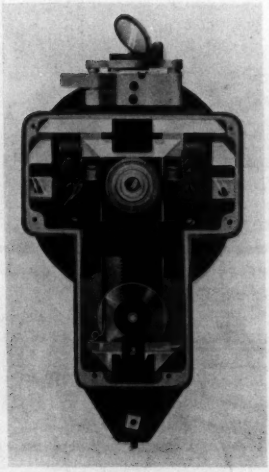


Fig. 10. Optical system for vertical circle.

The Glass Circles

Until quite recently it has been customary to cut the circle graduations on silver insets, partly because it is possible to cut a very clean fine line in this metal and partly because such lines show up well and are easily read. The main objections to the use of silver are, first that the surface tarnishes, particularly in sulphur-laden air, secondly that any dust settling on the surface of the silver is focussed sharply in the field of view, and thirdly that small movements of the silver insets undoubtedly take place and become more important as greater accuracy is sought.

If the graduations and figures are cut or etched on a glass surface they may be silvered over and read through the glass; it is then no longer possible for tarnishing to take place or for dust to settle in the plane of the graduations. Owing to the high reflecting value of a silver film it is possible to obtain excellent illumination and to see the graduations and figures standing out black against a white structureless background. If the glass is well annealed it will be quite free from internal strain and there will be no tendency to change of shape.

The commercial production of glass circles by an etching process has involved experiments to discover (*a*) the most suitable type of glass for etching, (*b*) a resist of a texture that allows very fine lines to be cut, that does not undergo perceptible change between the cutting of the first and the last line and that thoroughly protects the surface of the glass during the etching process, and (*c*) a cutting tool hard enough to resist wear and shaped so as to avoid clogging with particles of resist. The development of a suitable technique of etching soon followed. It is, of course, of fundamental importance that the 1080 graduations of each circle should be evenly spaced and of equal thickness. The spacing of the lines of the horizontal circle is almost exactly one-hundredth of an inch and a displacement of a graduation by one twelve-hundredth of this interval or 0·000008 of an inch will give rise to an error of one second at the centre of the circle. The thickness of the etched graduations is about 0·0002 of an inch. The figures must also be etched in their correct positions and present some difficulty as they are too small to be read by the naked eye and measure only 0·004 of an inch in height.

At one time it was thought that the lines might be cut in glass just as they may be cut in silver, and with a suitable tool it is possible to cut the most perfect lines in this manner. Each time the tool made a cutting stroke a small curly cutting of glass was removed and deposited beside the graduation, but unfortunately the edge of the tool invariably broke down after a maximum of two or three hundred lines had been cut in this manner.

During this development period certain of the etching problems were submitted to the British Scientific Instrument Research Association and one is pleased to record here the very valuable help and assistance that was almost immediately forthcoming. Owing largely to this help the various etching processes are now under complete control and glass circles are produced almost as easily as silver circles.

Tests for Accuracy

In order to test intelligently the accuracy of a theodolite it is necessary to disentangle the various errors to which faults of workmanship and adjustment give rise. If it is possible to do this with such certainty that independent observers may be expected to obtain similar results when calibrating the same instrument, then the results so obtained may be regarded as figures of merit which accurately represent a standard of performance to be expected from a particular instrument.

A comprehensive series of tests has been devised by Prof. H. J. Heuvelink*, with this object in view, and a careful analysis of the readings obtained enables figures of merit to be assessed and direct comparison to be made between different instruments.

When making the tests two collimators are set permanently at an angle slightly exceeding 45° and the theodolite is levelled and made to read slightly in excess of 0° in collimator *A*. It is then pointed on collimator *B* and the angle between the two collimators is measured in four series each of nine circle positions. Each angle measurement is made several times forwards and backwards and it thus becomes possible to separate errors due to faulty dividing from those due to faulty pointing of the telescope. The series of circle positions is then repeated in the reverse order and finally closes on the initial graduations. The circle positions are so chosen that the graduations utilised in each series are evenly distributed round the circle and are completely independent.

Owing to the method of reading the circles of the "Tavistock" theodolite the ordinary observation of a direction is free from eccentricity of the circle and consists of an observational error and a graduation error. The average total value of the latter is made up of a regular and an incidental part and the former may be represented by a Fourier series, though generally it is not necessary to separate the regular and incidental errors.

These tests have demonstrated the remarkable accuracy of the "Tavistock" theodolite as it has happened on several occasions that none of the 36 separate determinations of the collimator angle has differed from the mean by as much as one second. The total mean error, which includes instrumental errors and errors of observation, varies from a minimum of $\pm 0{\cdot}35''$ and the mean value for ten consecutive instruments was $\pm 0{\cdot}74''$.

The methods of Dr Heuvelink do not allow of the direct determination of the diametral errors of the circle, but these can be arrived at by a different method in which the collimators are set to some angle of which 360° is an even multiple—say 30°.

A series of readings is then taken which commences and terminates on the same graduations and from these it is easy to deduce the diametral errors, since all graduation errors must cancel out over 180°. The diametral errors of instrument No. Y 2167 were determined at every 10° by this method and one complete set of

* *Z. f. Instrk.* **45**, February 1925 (70–84).

readings formed the basis for the dotted line of the graph in Fig. 11, the total mean error having a value of $\pm$ 0·50″. With twice as many observations the mean error was reduced to $\pm$ 0·325″ and with three times as many observations to $\pm$ 0·287″.

Closing errors, losses in the centres and micrometers, the operation of the clamps and slow motions are all investigated during the final tests, which occupy about 8 hours.

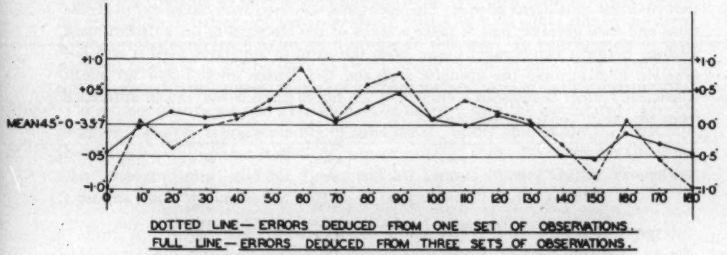


Fig. 11. Diametral errors, theodolite No. Y 2167.

DISCUSSION

Capt. T. Y. Baker: Images of the scale from opposite sides of the circle are brought into a common focal plane by the prism system described. The two images are separated by a datum mark which is itself in this focal plane. By tracing the light backwards we can imagine images of the datum mark on the scale itself. As the instrument is turned in azimuth the datum mark images move over the circle. Seen from the other end the images of the scale divisions move relatively to the datum mark. With the horizontal circle cut from 0° to 360°, as the instrument is turned in azimuth, the datum marks will both move to a higher reading *together*. The corresponding effect at the reading end is, on account of the way in which the prism reflections are arranged, that both scale images move to the left. If instead of moving the theodolite in azimuth the optical micrometer is operated, the datum mark images on the scale will both move to a higher reading and at the reading end the same effect is produced.

Suppose now without any movement of the micrometer and without any rotation of the theodolite the horizontal circle be given a slight displacement of its centre at right angles to the line joining the two reading points. Then one datum image will go to a higher reading, the other to a lower and by the same amount. From the reading end this means that one scale image is displaced to the right and the other equally to the left, so that if a correct setting has been previously made by bisecting the space between the two end scale divisions by the datum mark it will

still bisect them, though their separation is increased by the centering error. Thus it will be seen that the correct setting can be made independently of centering error or, in other words, the reading actually made is the true reading representing the mean of two made at opposite sides of the circle.

The acuity of the eye in making a setting of this type is good. Recently the Department of Geography at Cambridge have been kind enough to carry out for us a series of tests on some of the first year students to determine the type of acuity that could be considered normal. The apparatus was used with naked eye observations and each observer had to make a series of ten attempts to set a datum mark midway between two parallel lines. With the form of apparatus used it was not possible to determine the absolute zero and the figures given below are mean consistency rather than mean accuracy. Each figure given is the "mean difference from the mean" of ten observations.

	Left secs.	Right secs.	Alternate secs.
1	2·61	2·69	3·17
2	5·49	1·96	2·06
3	1·24	2·72	2·04
4	5·64	3·20	2·16
5	3·95	2·65	5·96
6	4·80	1·64	—
7	2·71	3·42	4·99
8	6·51	4·95	4·02
9	2·70	5·40	3·40
10	1·90	3·70	2·60
11	2·10	2·70	5·00
12	6·00	5·40	3·40
13	3·69	3·38	4·24
14	5·11	2·26	2·67

It is evident from these results that a mean consistency of three or four seconds at the eye is what may be expected of a normal moderately untrained observer. A skilled observer should get down, I think, to a mean consistency of two seconds. In the "Tavistock" theodolite the magnification of the reading microscope is such that mean consistency of reading should be about 0·1 second.

Major E. O. Henrici: I must congratulate all concerned on the production of this theodolite. There is one detail that may produce a noticeable error, viz., the electric lamps appear to be in very close proximity to the metal work of the instrument, and it would appear that unequal heating would be likely to result from their use. A very small distortion would be noticeable on an instrument reading to single seconds of arc.

Prof. L. C. Martin: Messrs Cooke, Troughton & Simms are to be congratulated on their courage in essaying such an ambitious construction, and I think that Capt. Baker and Mr Cheshire are also to be congratulated on their most ingenious reading device. I am rather amazed by the consistency which Capt. Baker shows to be possible in the settings, as the plain "coincidence" setting has always been generally assumed to be superior to other settings of this class, but evidently that assumption is not well founded.

Would it be possible in any special case to attach a fine-reading scale directly to the frame carrying the deflection prisms, and avoid the mechanical link with the fine-reading circle?

Mr T. F. Connolly: It may be of interest to mention my own procedure in making a fine vernier setting on a circle $4\frac{1}{2}$ to 5 inches in diameter and reading to 20 seconds of arc. A vernier setting is usually regarded as a "coincidence" judgment. I make the coincidence only as an approximation. My final judgment depends on my estimation of balance of *non*-coincidence of the lines on either side of the zero. I have greater confidence in my own setting in this way. In consequence of this personal equation it will be obvious that I prefer the balanced setting adopted in the "Tavistock" instrument to the coincidence method used in similar instruments.

I am not a surveyor and have no field experience with the instrument. I have, however, had several opportunities of handling it. In my opinion the "Tavistock" theodolite is a triumph for British instrument making. Capt. Baker and Mr Cheshire who "thought it out" and Mr Taylor and Mr Linn of Messrs Cooke, Troughton & Simms who "worked it out" are to be congratulated on the result.

Prof. A. F. C. Pollard: Messrs Cooke, Troughton & Simms are to be congratulated on producing this efficient and accurate instrument. There is, however, a small point which calls for comment in the design of the mechanism for coupling the travel of the prisms M to the rotation of the glass circle F. Coupling by rack and pinion as described, I should have thought, would introduce a periodic error, at least in the relative motion of slide and circle, unless the teeth of the rack and pinion had been made to the involute profile with extraordinary care and moreover with care beyond ordinary manufacturing possibility. In order that two components coupled by toothed gearing shall have even a reasonably constant velocity ratio, the profiles have to be finished by generation grinding. Therefore I would like to know if Mr Taylor has found any difficulties here either in the nature of troublesome error or of manufacture. If such is the case, may I suggest that the simplest way to obtain a constant velocity ratio is to replace the rack with a steel tape secured at one end to the sliding member and the pinion by a cylinder ground true, round which the other end of the tape is partly wound and secured? The cylinder will then roll upon the tape in the same way as the pinion on the rack. The practical application of such a wrapping coupling, of course, requires three tapes, one pulling in the same line and against but between the other two, by the tension of a strong spring.

Mr Taylor: The results of the tests carried out by the Department of Geography at Cambridge to discover the acuity of the normal unaided eye in making a straddle setting are very interesting and it is noted that Capt. Baker considers that a trained observer should be able to repeat such settings to a mean consistency of two seconds. It would be interesting to know the angle subtended at the eye by the apparatus employed, as this is also a matter of considerable importance.

Major Henrici calls attention to the internal position of the small electric bulb illuminating the horizontal circle and to the possibility of errors arising from local

heating of the instrument. Actually the small bulb fitted generates very little heat and if readings are taken immediately after switching on the lamp and others after it has been burning for some time no definite error due to this cause can be traced.

In reply to Prof. Martin it was not found practicable to attach the fine-reading scale directly to the frame carrying the deflecting prisms. The desirability of avoiding any unnecessary mechanical link between the frame and the fine-reading circle was fully realised and connection was made by a rack and pinion. The rack is pivoted at one end and held up to the pinion by a small spring which effectually eliminates backlash.

Mr Connolly refers to the methods he employs when setting verniers. The coincidence setting is then regarded as an approximation and "weight" is given to his estimate of balance between the broken lines on either side of zero. On making enquiries among our workmen engaged in the setting and reading of verniers it appears that about half adopt Mr Connolly's method and about half give "weight" to the coincidence of the zero graduations and regard the balance of the broken lines as only an approximate indication.

I have also to thank Mr Connolly on behalf of my firm and colleagues for his very generous praise of the "Tavistock" theodolite. It is particularly appreciated as coming from one so well acquainted with the design and construction of modern surveying instruments.

Prof. Pollard also refers to the mechanical connections between the deflecting prisms and the fine-reading circle and to the importance of very accurate gear cutting to secure a constant velocity ratio. Fortunately errors arising from this cause are easily isolated and measured and no very great difficulty has been experienced in securing the required degree of accuracy. The suggestion to replace the rack and pinion by steel tapes is ingenious and interesting and will be borne in mind for some future occasion.

THE EXPERIMENTAL PROOF OF A FUNDAMENTAL PHOTO-ELECTRIC LAW

By N. R. CAMPBELL

MS. received, 13th November, 1930. Read and discussed, 13th November, 1930.

(Communication from the Staff of the Research Laboratories of The General Electric Co. Ltd., Wembley, England.)

It is now certain that the primary electronic emission from a photo-electric cathode is proportional to the amount of radiation incident on it, the quality of the radiation being always the same. The apparent departures from this law that have been reported, and still are reported from time to time, are due either to a change in the quality of the radiation, or to mistaking for the primary electronic emission some current that is not really proportional to that emission, or to a change in the nature of the cathode produced by the radiation. But though this fundamental law has been established, the proofs of it are not logically satisfactory, because they rest upon the assumed truth of some other law that is really irrelevant; even if this law is actually true, its truth is not necessarily connected with that of the law it is used to prove, and circumstances can be imagined, if not realised, in which one law would be true but not the other. Thus in the experiments used to establish the photo-electric law, the quantity of radiation has been measured either by means of the inverse square law or the law of transmission through crossed nicols. But the meaning of quantity of radiation does not depend upon either of these laws; and though it may be admitted that there must be conditions in which each of them is accurately true, it has to be admitted also that these conditions are exceedingly difficult to realise; it is almost certain that they were not *completely* realised in the experiments.

My purpose in this note is to draw attention to a very simple method of establishing the law that is almost entirely free from these objections. But before we proceed to it, it may be well to consider another method which has already been proposed.

It has been pointed out that if the current is proportional to the light, the absorption coefficient of a filter, measured by means of a photo-electric cell, ought to turn out to be independent of the intensity of the light used to measure it. The experiment would be as follows. We throw a beam of light on the cell and note the reading (i_1) on a galvanometer receiving the resulting current. The filter is now inserted in the beam and the decreased reading (i_2) is noted. The filter is now removed, the galvanometer shunted, and the intensity of the beam of light increased till the reading is again i_1; the filter is inserted; if current is proportional to light, the reading now should be again i_2.

For, if $i(L)$ is the current corresponding to radiation L, and if α is the absorption coefficient of the filter, which is *ex hypothesi* independent of L, we have proved that

$$i(\alpha L)/i(L) = \beta \qquad \ldots\ldots(1),$$

where β is a constant independent of L. But β must be 1 when α is 1; consequently if (1) holds for all values of α, we must have

$$i(\alpha L) = \alpha \,.\, i(L),$$

which is the law we desire to establish.

The assumptions contained in the last sentence need not detain us long. They are, in effect, that i is a single-valued function of L and that, if the experiment succeeds for one filter, it will succeed for any similar filter; these assumptions are accessible to experiment. The apparent advantage of the method is that we seem to avoid the assumption of any numerical law, and to use only assumptions of equality and constancy. Thus we do not assume anything about the scale of the galvanometer; we assume only that, when a shunt is inserted, the currents corresponding to all deflections fall in the same ratio. But examination will show that, in making that assumption, we are in fact assuming Ohm's Law, which is a numerical law wholly irrelevant to the photo-electric law. Our assumption that the absorption coefficient is independent of the light is again the assumption of a numerical law, namely that the transmitted is proportional to the incident light. Moreover it is a law that is open to as much suspicion as the inverse square law. For how actually are we to change the intensity of the beam without changing the extent to which it is absorbed by the filter? If we try to change intensity without changing quality, it will be almost impossible to avoid changing slightly the path of the beam and therefore the part of the filter through which it passes. We may avoid changing the path by using an incandescent lamp and changing the intensity by means of the current through the filament. But then we change the quality; and though there are filters (such as blackened gauze) whose absorption coefficient must be very nearly independent of the quality, we cannot feel certain that it is quite independent.

Accordingly, though this method seems to me at least as good as, and indeed rather better than, the older methods of proving the law, it cannot be regarded as ideal. It is discussed merely to show what far-reaching assumptions may be latent in a very simple experiment.

Now let us turn to the better method, illustrated in the accompanying figure. The cell P is connected to an electrometer E, taking no current, and used only as a null instrument, for example a Compton electrometer or the grid of a well-designed valve amplifier. It is also connected to two resistances R_1, R_2, the other ends of which can be either insulated or maintained at any desired potential. The cell can be illuminated by either or both of two filament lamps L_1, L_2. It is first exposed to L_1, and the potential E_1 applied to R_1 adjusted, so that the photo-electric current is exactly balanced by the current through R_1 and the electrometer remains uncharged. L_1 is turned out and R_1 insulated; L_2 is turned on and the current due to it compensated by applying the potential E_2 to R_2. Both lamps are

now turned on and the potentials E_1, E_2 applied to both R_1 and R_2; the electrometer should still remain uncharged.

For, if it does, we must have, if L_1 and L_2 are the amounts of radiation received from L_1 and L_2,

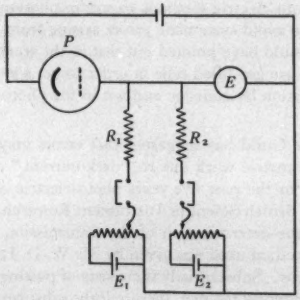
$$i(L_1 + L_2) = i(L_1) + i(L_2) \qquad \ldots\ldots(2).$$

It is easily shown that the only analytic function (i.e. one having a differential coefficient everywhere) satisfying this relation is

$$i(L) \equiv \beta L \qquad \ldots\ldots(3),$$

where β is independent of L. The only assumptions, other than that $i(L)$ is analytic, are these:

(1) The current through a resistance is determined wholly by the potential



difference between the ends of the resistance. No assumption is made about the form of the relation between current and potential difference, except that it is one-one.

(2) The current received by an insulated body from two conductors attached to it is the sum of those received from each.

(3) The light received by the cell from one lamp is independent of whether the other is emitting radiation.

The truth of (1) and (2) is implied in the very meaning of *current*; if they were not true, there would be no such conception as *current* in experimental physics. Assumption (3), on the other hand, is probably not exactly true. For some minute proportion of the radiation that P receives from L_1 will reach it by reflection from the filament of L_2, and vice versa. When the filament of L_2 is heated, its reflection coefficient will change and with it the light received by P from L_1. The error from this source must be exceedingly minute, and can easily be made far beyond the reach of detection. Assumption (3) is as nearly true as any law can be in actual

conditions; far more nearly true than either the inverse square law or the law of crossed nicols. And apart from this law, we have assumed nothing, the truth of which is not implied by the very terms we use.

(Owing to an unfortunate mishap the experiment was not actually demonstrated at the time, as had been intended. But it was demonstrated at the Annual Exhibition of the Physical and Optical Societies a few weeks later.)

DISCUSSION

Mr J. Guild: I should like to ask Dr Campbell if any correction is first made for dark current or fatigue effects before the linear relationship is obtained. In attempting to apply photo-electric methods to spectrophotometry it has been found exceedingly difficult to avoid systematic errors arising from such causes.

(*Added later.*) I should have pointed out that in the work to which I referred it has been necessary to use gas-filled cells in order to get adequate sensitivity. It is, no doubt, in the ionisation by collision and not in the photo-electric effect that the irregularities arise.

Dr H. Moore: Mr Guild has suggested that errors may arise in using photo-electric cells for photometric work due to "dark current" and other causes of an electrical character. For the past five years photo-electric cells have been used in the laboratories of the British Scientific Instrument Research Association for photometric work such as the determination of the transmission coefficients of glasses. A description of the method used was given by Mr W. D. Haigh in the *Proceedings of the Optical Convention*. Substantially it consists of putting the block of glass into the path of the light entering the cell, then quickly substituting for the glass a pair of adjustable neutral wedges calibrated so that their transmission for any degree of overlap is known. The overlap of the wedges is adjusted until the response of the cell is the same with the wedges in the beam as with the glass in the beam. The apparatus is arranged so that the block of glass and the wedges can be interchanged very quickly, and any number of times; the adjustment for balance (or equality of response of the cell) can thus be made with considerable accuracy. The transmission of the glass is then the same as the transmission of the wedges, and can be obtained, therefore, by observing the overlap of the wedges. It is considered that an accuracy of 1 in 1000 can fairly be claimed for this method. The electrical difficulties which arise are mainly due to surface leakage over the various parts of the apparatus; the "dark current" is entirely negligible. With the form of apparatus used and the experimental method employed any errors which might result from electrical causes are eliminated.

(*Communicated.*) The President pointed out that the photo-electric method of photometry used in the laboratories of the B.S.I.R.A. depends for its accuracy upon the sensitivity of the photo-electric cell being uniform over the photo-

sensitive surface. This is so to a small extent, owing to the slightly increased spread of the beam of parallel light when transmitted through the block of glass. This spread is due to the finite size of the source of light; the angle subtended at the parallelising lens by the diameter of the source is approximately 3°. As the President assumed, this matter has been carefully gone into and it has been amply shown that any error arising from lack of uniformity of the cells used is less than 1 in 1000. Any cell showing variations of response of this order over the area likely to be irradiated is rejected.

To give details of the way in which the cells are examined for uniformity is, perhaps, unnecessary; it is probably sufficient to say that agreement within 1 in 1000 is obtainable in observations taken with one and the same cell, using beams of different cross-sectional area and in observations taken with different cells. Moreover, observations on the same glasses, repeated after intervals of two or three years (the glasses having been repolished if necessary), showed the same order of agreement is spite of the fact that the apparatus during this interval had been taken down and re-erected several times.

ON THE DETERMINATION OF THE TRANSMISSION FACTORS OF COLOURED SIGNAL LENSES

By H. BUCKLEY, M.Sc., F.Inst.P.
(Photometry Division, The National Physical Laboratory.)

MS. received, 3*rd December*, 1930. *Read and discussed*, 11*th December*, 1930.

ABSTRACT. The paper gives a theoretical treatment of the problem of the determination of the transmission factors of coloured lenses such as are used for railway signalling purposes.

In the 1928 report* of the International Commission on Illumination's Committee on Coloured Glass for Signal Purposes, the following outline of a method of measuring the transmission factors of coloured lenses used in railway signals, is given:

"Measurement of lenses.

"On one side of the photometer is placed a clear comparison lens together with a coloured roundel of the hue of the lens under test (these are not removed during the test). On the other side is placed a clear glass lens of the same diameter and focus as the lens under test, together with a standard roundel of known value (transmission factor). It is considered essential that the lamps should be in opal bulbs in order that the photometer screen may be uniformly illuminated. The separation of the edges of the lenses is adjusted to 200 cm. and the centres of the light sources are placed behind the lenses at the proper focal distances.

"The photometer is placed in position to read the value marked on the standard (coloured roundel) and a photometric balance is obtained by adjusting one or both lamps with a rheostat. The clear lens and standard roundel are then removed and the coloured lens and a clear roundel substituted. The new position of the photometer for photometric balance gives the value (transmission factor) of the lens."

The underlying assumptions in this method appear to be that as the percentage reflection losses in the two systems compared in this way are the same, and as the clear lens and the clear roundel have equal absorptions, the photometric comparison of the two systems gives the transmission factor of the coloured lens relative to the transmission factor of the standard coloured roundel.

This deduction from the assumptions however is not correct. The information which the photometric comparison gives is:

(1) The ratio of the transmission factors of the two systems.

(2) The ratio of the transmittance of the coloured standard lens to that of the coloured standard roundel on the further assumption that

(α) the percentage reflection losses for the coloured roundel and the clear roundel are the same;

(β) the percentage reflection losses for the coloured lens and the clear lens are the same.

* *Comm. Int. de l'Éclairage Sept. Sess.* p. 806. 1928.

The percentage reflection losses for a lens are, however, different from those of a roundel. In consequence the transmission factor of the coloured lens cannot be deduced from the photometric comparison unless the percentage reflection losses for a lens and for a roundel are known.

Analytically this is shown as follows:

Let R_l = reflectance of the coloured lens,
R_r = reflectance of the coloured roundel,
T_l = transmittance of the coloured lens,
T_r = transmittance of the coloured roundel,
$t_l = (1 - R_l)\, T_l$ = transmission factor of coloured lens,
$t_r = (1 - R_r)\, T_r$ = transmission factor of coloured roundel.

R_l', R_r', T_l', T_r', t_l' and t_r' are the corresponding quantities for the clear lens and clear roundel.

With a fixed photometer and a fixed constant light source used with the two systems which are compared with the clear comparison lens and coloured roundel, the illumination of the photometer is as follows:

For system I—clear lens and standard coloured roundel,

$$I_1 = k\,(1 - R_l')\, T_l'\,(1 - R_r)\, T_r,$$

where k is a constant.

For system II—coloured lens (under test) and clear roundel,

$$I_2 = k\,(1 - R_l)\, T_l\,(1 - R_r')\, T_r'.$$

Hence
$$\frac{I_2}{I_1} = \frac{(1 - R_l)\,(1 - R_r')\, T_l T_r'}{(1 - R_l')\,(1 - R_r)\, T_l' T_r} = \alpha.$$

It is reasonable to assume that the percentage reflection losses for the coloured lens are the same as those for the clear lens, since the lenses have the same form, and reflection losses at air-glass and glass-air surfaces are practically independent of the wave-length of the light used.

Thus
$$R_l = R_l'.$$

Similarly
$$R_r = R_r'.$$

Hence
$$\frac{T_l T_r'}{T_l' T_r} = \alpha.$$

If it be assumed that the clear lens and the clear roundel have either no absorption or equal absorptions

$$T_l' = T_r',$$

so that
$$\alpha = T_l / T_r,$$

i.e.
$$T_l = \alpha T_r;$$

$$\therefore\ (1 - R_l)\, T_l = \frac{\alpha T_r\,(1 - R_l)\,(1 - R_r)}{(1 - R_r)}.$$

Hence
$$t_l = \frac{\alpha t_r\,(1 - R_l)}{(1 - R_r)}.$$

Thus the expression for t_l involves R_l and R_r in addition to α (which is found from the photometric comparison) and the known transmission factor t_r of the standard roundel.

In the case of a clear step lens used in railway signalling the reflection losses were found at the National Physical Laboratory to be about 14 per cent., while the reflection losses from a polished plate of optical glass would be about 8 per cent. according to Fresnel's formula.

Thus
$$t_l = \alpha t_r \, 0{\cdot}86/0{\cdot}92$$
$$= 0{\cdot}935\alpha t_r .$$

The method outlined at the beginning of this note would have given
$$t_l = \alpha t_r ,$$
which is in error by about 7 per cent. For other types of signal lens the reflection loss would of course be different from the 14 per cent. mentioned above.

Experiments at the National Physical Laboratory have shown that for certain clear lenses the actual absorption of light was about 1 per cent. to 2 per cent., while for a clear piece of optically worked glass the absorption was about 0·5 per cent. This necessitates a further correction amounting to about 1 per cent., so that
$$t_l = 0{\cdot}925\alpha t_r .$$

DISCUSSION

Mr T. Smith: The chief difficulties in the problem Mr Buckley has discussed are attributable to the absence of precise definitions of the magnitudes under consideration. The definitions must be framed with a view to the conditions of test and of use. The introduction of transmittances does not appear to be helpful.

The equation
$$\frac{I_2}{I_1} = \frac{t_l t_r'}{t_l' t_r}$$
is sufficiently near the truth, and t_l/t_l' would then follow from a direct determination of t_r/t_r'. The use of reflection factors in the rather loose way customary in theoretical discussions of photometric problems is somewhat dangerous, for in general to a definite transmission factor there does not correspond a single reflection factor.

Mr Buckley: Mr Smith is quite correct in stating that the ratio t_l/t_l' would follow from a direct determination of the ratio t_r/t_r'. What is wanted, however, is the actual value of t_l when t_l' is different from unity on account of absorption and reflection losses in the clear lens. The absorption loss is relatively easily determined; the determination of reflection losses is difficult. By using "transmittances" instead of "transmission factors" the difficulty is avoided.

It would certainly be useful if there were precise definitions of these and other related magnitudes connected with the passage of light through non-parallel sided media.

INTERPOLATION FORMULAE FOR THE REFRACTIVE INDICES OF GLASS

By Mrs E. GIFFORD

(Communicated by the late Colonel J. W. Gifford.)

MS. received, 27th August, 1930. Read and discussed, 11th December, 1930.

ABSTRACT. Formulae for the refractive indices of glasses for five lines are given, making use only of the measured indices for the *C*, *D*, and *F* lines of the spectrum. A particular feature of the formulae is the simplicity of the numerical coefficients which renders the calculations extremely easy and rapid. Particulars are given of the errors found in the application of the formulae and numerical examples are included.

Every lens computer bases his work on the values of the ratio $(\mu - 1)/\delta\mu$ computed from measurements of the refractive indices for definite spectral lines. As optical glass makers generally give the refractive indices of their glasses for the lines *C*, *D*, and *F* only, computers use the ratio $(D - 1)/(F - C)$. In a paper* read before this Society in 1924 my husband showed that these lines were not the best with which to compute a lens. He took the value of $\mu - 1$ for the lead line of wave-length 5609 Å. because it is in the part of the spectrum for which the eye is most sensitive; the Germans prefer the mercury line of wave-length 5461 Å. For $\delta\mu$ he used the lines *E* and *D* for a visual lens, the cadmium line 4678 Å. and the lead line 5609 Å. for a photographic lens, and the same cadmium line and the helium line 7066 Å. for a triple objective. Here then are five lines for which the lens computer should know the indices. If he has no spectroscope nor the requisite skill to use it, he must fall back on some interpolation formula. Such formulae are, as a rule, rather lengthy and difficult to use, they do not give very accurate results, and they depend on determinations of wave-lengths which, so far as I know, have not been observed as frequently nor measured as accurately as have refractive indices. It is obvious that the variation in index of any glass for any particular part of the spectrum must be somewhat similar to that of any other glass. Thus, if the indices for the lines *C*, *D*, and *F* are given, we should be able to obtain the indices for the other lines with more or less accuracy.

I worked out refractive index formulae for the five lines helium 7066 Å., lead 5609 Å., mercury 5461 Å., iron (*e*) 5270 Å., cadmium 4678 Å., adopting $\mu - 1$ as the variable instead of μ. For the lead, mercury and iron lines interpolation

* J. W. Gifford, *Trans. Opt. Soc.* **25** 1923–24 (123).

is needed, because they come between the D and F lines. On the other hand extrapolation is needed for the helium and cadmium lines; the results for these are therefore less accurate than for the other three lines. My formulae are as follows:

Line	$\mu - 1$
Helium 7066	$C - 0{\cdot}15\,(F - C) - 0{\cdot}0004\,C$
Lead 5609	$\frac{1}{3}\,(C + D + F + 0{\cdot}001\,C)$
Mercury 5461	$\frac{1}{3}\,(2D + F) + 0{\cdot}0002\,C$
Iron 5270	$\frac{1}{2}\,(D + F) + 0{\cdot}0002\,C + 0{\cdot}011\,(F - C)$
Cadmium 4678	$F + 0{\cdot}201\,(F - C) - 0{\cdot}0004\,C$

where $C = \mu_C - 1$, $D = \mu_{D_a} - 1$, $F = \mu_F - 1$.

These formulae may look clumsy, but they are arranged so that they can be used without logarithms or calculating machine. Of course only two or three significant figures in the values of C or $F - C$ need be used in the small correcting terms.

I applied these formulae to some of the results given by my husband in a paper* he read before the Royal Society in 1912. He gave the indices for thirteen lines for twenty-seven glasses, arranged in the order of their mean dispersion $F - C$, beginning with the lowest. I selected sixteen of these glasses, the first and last and fourteen intermediate glasses having more or less equally spaced dispersions; they were not chosen because they were likely to be easy to calculate. The eighty calculated indices were compared with the observed values and the greatest error was 0·000052. Forty of the errors, that is one-half of the total, were less than 0·00001 and twenty-four were less than 0·000005. These results compare favourably with those obtainable with any other interpolation formula I know. The average and greatest errors for the different lines were as follows:

Wave-length	7066	5609	5461	5270	4678
Average error	0·000023	0·000008	0·000011	0·000011	0·000017
Greatest error	0·000052	0·000020	0·000036	0·000038	0·000048

I was led to construct these formulae through a suggestion made by Mr Nelson, late President of the Royal Microscopical Society, who proposed the use of the mean of the indices for the C, D, and F lines as a mean index.

The following examples show the way in which I have found it most convenient to arrange the calculation. The glasses are a boro-silicate crown and a dense flint, the data being:

Crown	$C = 0{\cdot}509894$	$D = 0{\cdot}512288$	$F = 0{\cdot}517937$	$F - C = 0{\cdot}008042$
Flint	$C = 0{\cdot}607418$	$D = 0{\cdot}612137$	$F = 0{\cdot}623982$	$F - C = 0{\cdot}016564$

* J. W. Gifford, *Proc. Roy. Soc.* A, **87** 1912 (189).

Wave-length	Crown	Formula	Flint
7066 Å.		$C - 0{\cdot}15\,(F - C) - 0{\cdot}0004\,C$	
	0·0008042	$0{\cdot}1\,(F - C)$	0·0016564
	0·0004021	$0{\cdot}05\,(F - C)$	0·0008282
	0·0002040	$0{\cdot}0004\,C$	0·0002430
	0·0014103	Sum	0·0027276
	0·509894	C	0·607418
	0·508484	Computed value	0·604690
	0·508483	Observed value	0·604699
	+ 0·000001	Error	− 0·000009
5609 Å.		$\frac{1}{3}\,(C + D + F + 0{\cdot}001\,C)$	
	0·509894	C	0·607418
	0·512288	D	0·612137
	0·517937	F	0·623982
	0·000510	$0{\cdot}001\,C$	0·000607
	3)1·540629	Sum	3)1·844144
	0·513543	Computed value	0·614715
	0·513537	Observed value	0·614712
	+ 0·000006	Error	+ 0·000003
5461 Å.		$\frac{1}{3}\,(2D + F) + 0{\cdot}0002\,C$	
	0·512288	D	0·612137
	0·512288	D	0·612137
	0·517937	F	0·623982
	3)1·542513	Sum	3)1·848256
	0·514171	$\frac{1}{3}$ Sum	0·616085
	0·000102	$0{\cdot}0002\,C$	0·000121
	0·514273	Computed value	0·616206
	0·514282	Observed value	0·616196
	− 0·000009	Error	+ 0·000010
5270 Å.		$\frac{1}{2}\,(D + F) + 0{\cdot}0002\,C + 0{\cdot}011\,(F - C)$	
	0·512288	D	0·612137
	0·517937	F	0·623982
	2)1·030225	Sum	2)1·236119
	0·515112	$\frac{1}{2}$ Sum	0·618059
	0·000102	$0{\cdot}0002\,C$	0·000121
	0·000088	$0{\cdot}011\,(F - C)$	0·000182
	0·515302	Computed value	0·618362
	0·515303	Observed value	0·618368
	− 0·000001	Error	−0·000006
4678 Å.		$F + 0{\cdot}201\,(F - C) - 0{\cdot}0004\,C$	
	0·517937	F	0·623982
	0·001616	$0{\cdot}201\,(F - C)$	0·003329
	0·519553	Sum	0·627311
	0·000204	$0{\cdot}0004\,C$	0·000243
	0·519349	Computed value	0·627068
	0·519351	Observed value	0·627065
	− 0·000002	Error	+ 0·000003

DISCUSSION

Mr T. Smith: Those who from time to time make use of the current knowledge of variations of refractive index in glasses, quartz, and some other materials, and those who utilise tables of trigonometric functions to many decimal places, have no need to be told of their indebtedness to Colonel and Mrs Gifford. It is a very real pleasure to me to have the opportunity of expressing to Mrs Gifford our appreciation of her work and to thank her for her present communication. At the moment some of the formulae are not expressed in the manner most likely to be immediately understood by the average reader, but the examples show clearly the way in which the calculations should be carried out. I think it would be generally advantageous if Mrs Gifford would permit her formulae to be printed in a slightly modified form to prevent any misunderstanding*.

I have lately done a good deal of work on interpolation formulae for refractive indices, and I agree with Mrs Gifford that those in general use are insufficiently accurate and at times very dangerous when applied to optical glass. I shall be much interested in comparing Mrs Gifford's results with my own.

* [This has been done in the paper as printed. Ed.]

DEMONSTRATION OF THE VICKERS' PROJECTION MICROSCOPE

By R. L. SMITH, F.C.S.
(Messrs Vickers-Armstrongs, Ltd.)

Demonstrated and discussed, 16th October, 1930.

The new model Vickers' Projection Microscope has been evolved in the research laboratory of Messrs Vickers-Armstrongs Limited, Erith, with the object of producing an instrument possessing numerous valuable features which are not obtainable with microscopes and metallographs generally.

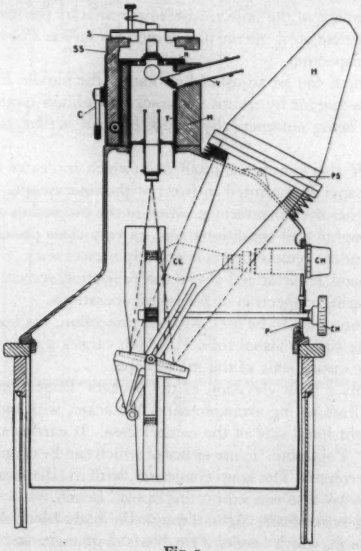


Fig. 1.

It consists of a heavy cast iron body block *M* (see Fig. 1), through which passes, vertically, a large diameter hole, bored to take a heavy tube *T*. The upper end of this tube is fitted, internally, with an adapter for the objective and, externally, is

threaded to engage with a nut *N* of large diameter. The under surface of the nut *N* rests upon the flat top of the block *M*, thereby supporting the tube *T* with its objective. The fine-focussing adjustment is secured in a particularly robust and satisfactory manner by the partial rotation of this nut.

The objective adapter consists of a brass ring, to which is secured two semi-circular plate magnets. Magnetic centering mounts are supplied, which can be fitted to ordinary objectives of any make. These magnetic adapters are particularly convenient for rapid and extremely accurate manipulation.

The stage *S* is mounted upon a heavy cast iron stage support *SS*. This stage support engages with the microscope block *M* by means of sliding faces, its elevation being controlled by rack and pinion movement. The close engagement of the working faces is ensured by a heavy clamping spring and locking screw *C*.

The microscope is mounted upon a very substantial cast iron camera case immediately above an adapter, which serves to carry a sliding microscope tube with projection eyepiece.

The projected image of the object, cast downwards by the inverted microscope, is reflected by a rustless steel mirror to a projection screen *PS*, mounted at a convenient angle for inspection.

The camera length can be adjusted by rotating the handle *EH*, which controls the elevation of the mirror by means of a rack and pinion motion, the projection screen and mirror being automatically tilted, by cam action, to suit the varying conditions.

The handle *EH* also controls a small dial, which indicates the camera length upon the control panel *P*, mounted in front of the microscope.

It will be seen that the convenient position of the projection or focussing screen is maintained throughout all conditions, and its very close proximity to the object and microscope renders remote controls entirely unnecessary.

A removable hood *H*, arranged above the projection screen, serves to exclude extraneous light during inspection or focussing operations.

When the microscope is to be used without projection, the hood *H* is swung out of position, and the sliding visual tube *V*, which carries a mirror and eyepiece, is introduced into the optical axis of the microscope.

Fig. 2 represents a front elevation of the Vickers' Projection Microscope, and shows clearly the illuminating arrangements. A bracket, with optical bench *OB*, is mounted at the right-hand side of the camera case. It carries a clockwork-driven arc lamp and also a "Pointolite" lamp, either of which can be changed over instantly, according to requirements. The lamp condenser, with iris diaphragm, water trough, and colour screens, are also carried on this optical bench.

A hole, passing horizontally right through the body block *M* serves to house, on the right, a tube *D*, which carries a small iris diaphragm and field lens, and, on the left, a sliding tube *L*, which is fitted with a vertical illuminator and a centering screen. This system is, of course, for vertical illumination of opaque objects.

The entire illuminating unit on optical bench *OB* can be elevated by means of a rack and pinion motion *OH*, to suit any type of illumination that may be required.

On the right-hand side of the camera and projection screen *PS* is a comparison chamber and screen *CS*. This chamber is illuminated and is used for viewing photomicrographic transparencies or auto-chrome transparencies of standard materials comparatively with the projected image of the object under inspection. The rotation of control handle *CH* enables the intensity of illumination of the transparency to be adjusted until it balances that of the projected image on the screen *PS*. By this means it is possible to inspect test specimens of any class very rapidly, with great accuracy, and without the formality of taking too many photographs.

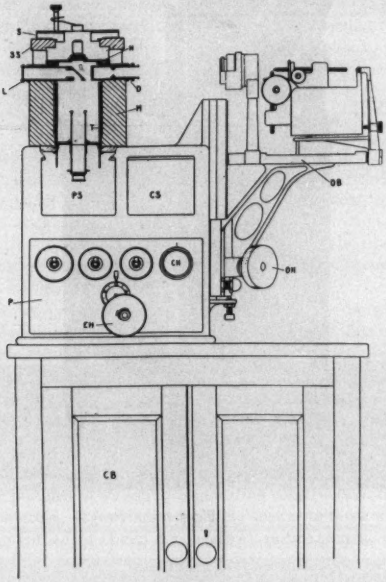


Fig. 2.

The control handle *CH* is also fitted with a graduated scale which serves to indicate the exposure necessary when a photomicrograph is required.

When the instrument is to be used with transmitted light, a mirror at 45° and stage condenser are attached above the object stage, as shown in Fig. 3.

The whole instrument is supported upon, and partly enveloped by, a substantial mahogany cabinet which carries all accessories, thereby making the entire unit complete in every respect.

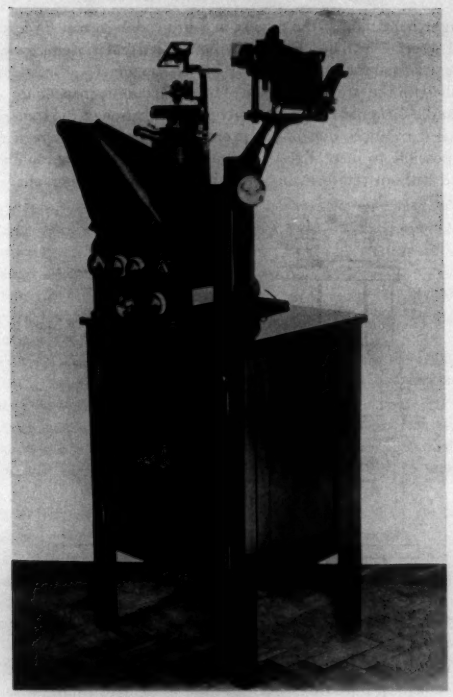


Fig. 3.

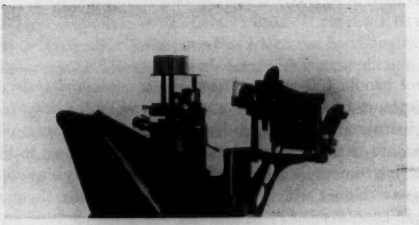


Fig. 4.

Perhaps the most outstanding feature of this instrument, apart from its unconventional appearance, is its immense robustness and immunity from differential vibration. This essential quality is possessed entirely by virtue of its design and not by the usual expedient of supporting the instrument upon shock-absorbing devices, all of which are more or less unsatisfactory. It is so robust and rigid that specimens up to 50 lb. in weight can be examined without the slightest damage to the instrument, and excellent photomicrographs can be obtained, at any magnification, irrespective of external vibrations.

This instrument is available for magnifications ranging from 3 to 5000 diameters. When used for very low power work, the objective and projection eyepiece are removed and replaced by a suitable type of camera lens. The object, in such cases, is supported upon a super-stage (see Fig. 4) and can be illuminated by vertical, oblique, or transmitted light, according to requirements.

DISCUSSION

Mr F. Twyman: British manufacturers of optical instruments will be grateful to Mr Smith for having designed this microscope. It seems to possess three novel features: a rigidity which enables it to be used without detriment to definition even in places where it would be subjected to great vibration; a strength which permits massive pieces up to 20 kilogrammes or more in weight to be examined without damage to the instrument or impairment of focussing; and arrangements for placing side by side with the image a comparison photograph. Not only are these features valuable in the laboratory, but in industry they will bring microscopical observation directly to the aid of those handling plant and materials, and thus introduce vision and knowledge into regions of Works' control heretofore administered by rule of thumb and prejudice. Although the instrument has been designed in connection with metallurgical work, it seems well fitted for use wherever the quantity of microscopical work to be done justifies the installation of an instrument permanently ready for use.

Prof. R. C. Gale: The projection microscope described by Mr Smith appeals to me chiefly on the grounds of its sound engineering construction, rigidity, and absence of remote controls. It provides a complete answer to those who claim that it is necessary to go abroad to obtain a satisfactory metallographic outfit, and at a reasonable price.

Mr Smith: I wish to thank Prof. Gale and Mr Twyman for their comments. It is particularly pleasing to note that both these gentlemen hold the opinion that we have here a small addition to the ever-growing list of British optical instruments which can claim definite advantages over the foreign products. Speaking generally of British instruments, I wish to take this opportunity of expressing the hope that British manufacturers in various industries will, in the country's interest as well as their own, make fuller use of the fine range of excellent British instruments which are now on the market in order to enable them to produce their commodities to the highest standard of quality and under scientifically economical conditions.

DEMONSTRATION OF THE USE OF THE SPECTROGRAPH IN METALLURGICAL ANALYSIS*

By D. M. SMITH, A.R.C.S., B.Sc., D.I.C.

(British Non-Ferrous Metals Research Association.)

Demonstrated and discussed, 13th November, 1930.

The technique of metallurgical analysis by the method of arc spectra, using two electrodes of the sample under test, was demonstrated by means of Hilger equipment for this purpose.

The various operations, aligning the light source with the axis of the collimator, focussing the image on the slit (or the prism face in the case of the logarithmic sector method), adjusting the slit width and the exposure of the plate, were described, while the following spectra were photographed and developed on the lecture table.

(*a*) *Comparison spectra.*

Cadmium,
Spelter,
Pure Zinc.
(Illustrating the identification of impurity lines.)

(*b*) *Logarithmic sector method.*

Copper sample.

While the plates were being developed, a brief survey of the various methods proposed for *quantitative* analysis by means of both arc and spark spectra was given, and it was shown how the modern methods have developed in a logical sequence from the earlier methods of correlating the appearance of impurity lines in the spectra with the percentage of impurity present.

When standardised with regard to optical and electrical conditions, the *method of direct comparison* of the spectra with those of standard alloys gives quantitative results of considerable accuracy, especially in the region of small quantities of impurities. Except in the case of testing to specification, this method generally requires the collection of comprehensive series of standard alloys.

The first "absolute" method proposed (i.e. by means of which, after the preliminary standardisation of the spectra, the standard alloys are no longer required for comparison purposes) consists of the use of *internal intensity standards*

* By kind permission of the Director of the British Non-Ferrous Metals Research Association.

(W. Gerlach). Suitable lines in the spectrum due to the main constituent are compared with impurity lines, and equality of intensity between pairs of such lines is correlated with the percentage of impurity present.

Where sufficient internal intensity standards are not available in the spectra, the number of such standards can be artificially increased by the *superposition of an auxiliary spectrum* of some suitable metal or alloy (W. Gerlach and E. Schweitzer). The auxiliary spectrum is coupled with the spectrum under investigation by the equality of intensity of two lines, one in each spectrum, this being effected by varying the relative times of exposure of the two spectra.

Methods of this type are limited by the extent to which small variations in the intensities of the lines can be detected visually. Recent developments, therefore, have been in the direction of *numerical* estimations of the intensities of the lines.

T. Negresco describes the use of a *microphotometer* whereby galvanometer deflections corresponding to the intensities of the lines are photographically recorded. Placing a *neutral wedge* in front of the spectrograph slit causes the lines to diminish in intensity to extinction, the length of the lines thus obtained furnishing a quantitative indication of their intensities. More recently, G. Scheibe and A. Neuhäusser have employed a *rotating sector* in which the aperture decreases logarithmically, the spectra obtained by this method being similar in appearance to wedge spectra. In these methods, the "internal standard" method of analysis is applied, the numerical comparisons of intensities giving refinement of accuracy on account of the estimation of the intensity being reduced to the measurement of a length.

The preparation of the spectrograms obtained during the demonstration having been completed, the plates were then projected as lantern slides and briefly discussed with reference to the methods of analysis outlined above.

Important advantages of the spectrographic method as compared with chemical methods for metallurgical analyses were thus shown to be simplicity and speed of operation and certainty of the results, especially for the determination of small quantities of impurities. Analyses, such as the estimation of traces of cadmium in zinc, calcium in magnesium, impurities in lead, etc., for which the usual chemical methods are admittedly tedious and uncertain, were referred to as examples of a wide and increasing scope of application of spectrographic methods.

The writer wishes to thank the President for the invitation to give this metallurgical demonstration, and Mr E. S. Dreblow for his skilful manipulation of the apparatus.

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SMITH, D. M. "The spectrographic determination of cadmium, lead and iron in zinc." *Trans. Faraday Soc.* **26** 1930 (101). Contains a tabular summary of the various methods available for metallurgical analyses.

NEGRESCO, T. *Recherches expérimentales d'analyse spectrale quantitative sur les alliages métalliques.* (Thèse, Les Presses Universitaires de France, June 1927.)

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DISCUSSION

Mr H. Buckley: I was much interested in Mr Smith's method of determining the intensities of spectrum lines and wondered if Mr Smith had tried the method which I once heard described by Dr Slade at a meeting of the Royal Society some years ago. The method consisted of alternately producing positives and negatives from the original negative. Each process increased contrast and after two or three positives had been produced it was found that the spectrum lines finished quite abruptly and their lengths could be quite easily measured.

Prof. R. C. Gale: I would like to ask Mr Smith whether his method is applicable to the complete analysis of lead, i.e. the determination of silver, iron, copper, antimony, bismuth, etc., in small quantities. The methods at present in use are with a few exceptions long and tedious, but it is essential that any new methods shall be at least as accurate.

Mr J. Guild: It is important when employing either a density wedge or a logarithmic sector at the slit of a spectrograph to ensure not only that the slit is uniformly illuminated throughout its length, but also that the effective aperture of the optical system of the spectrograph is the same for light from all parts of the slit. If the method is used with a spectrograph not provided with special stops to ensure this condition serious errors may arise from vignetting of the beams from the end regions of the slit by the boundaries of the lenses, prism, or other obstructions. The effective aperture, for such work, should be limited by a single diaphragm which is completely filled by light from all parts of the slit. In the arrangement demonstrated by Mr Smith, the vignetting difficulty is overcome by focussing an image of the source at the prism. When the source is small, does not this occasion too much loss of resolving power?

Prof. L. C. Martin: An interesting point arises out of the question asked by Mr Guild, i.e. whether Messrs Adam Hilger's proposal to focus the source of light in the collimator lens of the spectrograph when used with the logarithmic sector will not entail a serious loss in resolving power, since but a portion of the collimator lens will be illuminated by such an image.

I do not think the resolving power of the instrument will be likely to suffer as greatly as might be expected. The question involves a study of the conditions obtaining in an experiment first arranged, I believe, by Johnstone Stoney and discussed by the late Lord Rayleigh under the heading of "An optical paradox"*. In this experiment the image of a "point source" of light is projected by a lens *A*

* *Phil. Mag.* **9** 1905 (779–81).

into the aperture of a second lens *B*. This second lens projects an image of *A* on to a suitable screen. Owing to the small aperture of *B* which is apparently receiving light, it might be expected that the definition of the image of *A* would be very poor, but, as Lord Rayleigh remarks, the *definition* is apparently as good as when the whole aperture of *B* is illuminated by light from *A*.

In another experiment of Stoney's, lens *B* above is replaced by a grating, and the image of the sun is projected into the grating. It might be argued that the various parts of the grating are then illuminated by incoherent light and that no sharply defined images of lens *A* should be produced. Stoney demonstrated that, at least when lens *A* is reduced in aperture by the use of a slit diaphragm, the full resolving power of the grating is maintained. He might have demonstrated the same thing for the images of lens *A* produced without the use of the slit diaphragm; and also when the image of a star is projected into the grating instead of the sun, so that only a very small width of the grating is illuminated. The proof of this rests on a paper of my own*.

The explanation of these results on Huygens' principle may be attributed to the influence of the lens or grating on the secondary wavelets which illuminate its *whole* aperture irrespective of the apparent concentration of energy due to the particular phase relations of the components.

There is, of course, the known fact that, when in a microscope a grating object is illuminated by a condenser beam of indefinitely narrow angular aperture, the "resolving power" is diminished to one-half of that characteristic of illumination of full angular aperture. The conditions of Messrs Hilger's arrangement do not quite correspond to any of the above cases; yet it is possible to forecast that the definition will not suffer by anything like the serious extent which might at first sight be expected through the concentration of light in the collimator lens. Those who expect such a reduction forget the "dark space" controversy about the microscope. It may be asked why we use lenses at all to illuminate the slit. The question is not, however, the *reductio ad absurdum* for the above ideas. The use of lenses is mostly desirable, firstly, because one can usually obtain a brighter image unless a broad source is in use, and secondly, because the lenses of the spectroscope or spectrograph system often have residuals of aberration which cause nasty displacements of the lines if these lenses are not fully and symmetrically illuminated. In the use of the logarithmic sector the illuminating lens has to act as a source of uniform intensity.

We must not, of course, forget the vital distinctions between spectral resolving power and geometrical resolving power in these problems. The conditions which lead to apparent "resolution" of a regular structure in the geometrical sense may not apply in discussing the resolution of images in different wave-lengths. At any rate the whole problem needs careful examination; the truth of the matter is not self-evident.

Mr J. Guild: The difference between Prof. Martin's view and mine on this question of resolution appears to arise from a different usage of words. I used

* *Proc. Phys. Soc.* **43**, Part 2, 1931 (186).

"resolving power" in a loose sense to denote the spectral purity obtainable with slit widths of the order used in work of this kind, in which the diffraction effects of the slit are confined within a comparatively small zone surrounding the geometrical boundary of the beam. Prof. Martin, however, was obviously thinking of the ultimate resolving power of the system, which is only realised with an infinitesimal slit width. Whatever the geometrical configuration of the incident beam may be, the full resolving power corresponding to the aperture of the system beyond the slit will be realised if the slit is sufficiently narrow that the central band of its diffraction pattern fills the whole aperture (in a direction perpendicular to the slit) in an approximately uniform manner. But in these circumstances the essential feature of the arrangement under discussion, namely concentration of the beam in the middle of the aperture, no longer obtains. Further, such narrow slits are not practicable in work of this kind on account of inadequate light. Under the practical conditions which hold in such uses of spectroscopic apparatus the effective aperture is, roughly speaking, bounded by the geometrical outline of the beam, and, when this is small, loss of spectral purity is involved.

Mr Smith: In reply to Mr Buckley, I have not tried the method of alternate production of positives and negatives from "wedge" spectra, as it requires considerable time for its execution. This method would probably prove very useful for the investigation of special cases, but when routine metallurgical analyses are being carried out, the time-factor is important and one has to remember that when comparing the relative merits of spectrographic and chemical methods the question of the time taken is often the deciding factor. It seems, therefore, that the best methods, from this point of view, of overcoming the difficulties of determining the end-points of the gradually fading lines will be those methods in which the eye-strain caused by prolonged measurements is reduced to a minimum.

T. R. Merton* has proposed such a method in which the negative is enlarged through a process screen. The spectral lines are then divided into a series of dots and it has been found easier to determine the last dot visible than the end of a line which gradually decreases in intensity.

In reply to Prof. Gale, the spectrographic method is readily applicable to the determination of small quantities of metallic impurities in lead. Quite generally, it is the determination of small quantities of impurities (in so far as it is possible to detect them) in all metals and alloys where the spectrograph is shown to such advantage, as compared with chemical analysis. Once the method has been standardised by reference either to accurately analysed samples or, preferably, to synthetically prepared alloys, it can be applied to the routine assay of the metals and alloys investigated (using the "absolute" methods discussed during the demonstration). Moreover, it is in the region of small quantities where errors are liable to be introduced by the various and tedious manipulations required in the chemical analysis of such metals as lead and zinc (especially the determination of cadmium in the latter). The spectrographic method, on the other hand, will give *certain* results, within the

* *Proc. Roy. Soc.* A, **113** 1927 (697).

limits of accuracy attainable, and will not give such gross errors as are sometimes encountered in the chemical determination of very small quantities of impurities (due, for example, to masking effects by the preponderance of the main constituent and the presence of other impurities).

Mr Guild and Prof. Martin have discussed the question of loss of resolving power, when the image of the source is focussed on the prism face, from an optical point of view, and while I appreciate the various points raised, I view the problem more particularly from the practical aspect. For the spectral lines used in metallurgical spectrography, the resolution, or perhaps it would be better to say the definition, under these conditions is ample for the purpose and any loss of such is not appreciable.

Moreover, Prof. Martin states that "the use of lenses (to illuminate the slit) is mostly desirable," whereas Drs W. Gerlach and E. Schweitzer recommend the absence of any condensing lens in the photography of spark spectra. They claim that when no condensing lens is used the lines are obtained with perfectly uniform intensity along their length and the spectra are reproducible as regards the relative intensities of impurity lines and lines due to the main constituent of the metal or alloy under examination. This is obviously of great importance from the point of view of quantitative metallurgical spectrography. Although these methods of illumination are most probably unorthodox optically and theoretically, under standardised conditions they yield the desired practical results.

REVIEW

Strahlenoptik. By Dr M. HERZBERGER. Pp. xiii + 196; 60 Figs. (Berlin: Julius Springer, 1931.) Price RM. 18; gebunden RM. 19.40.

Optical workers will welcome the appearance of this timely book from the pen of Dr M. Herzberger, whose name is already familiar through the contributions he has made in recent years to the theory of optical instruments. Though the treatment is complete in the sense that the elements upon which the structure rests are fully treated, the emphasis rests upon modern contributions to optical theory. The outstanding feature of the book is the way in which results established by different workers using various methods are brought into line, developed on a common basis, and expressed in a single notation.

As the title indicates, the discussion does not go beyond the scope of ray theories of image formation. Within these limits the treatment is as complete as could be expected in a volume of this size. The starting-point is the stationary value of the path—to a modern writer no other choice is likely to be nearly as acceptable. In addition to chapters on such familiar grounds as the Gaussian theory and the Seidelian aberrations, the various exact forms of imagery known to us are carefully investigated, and are followed by investigations on the more desirable forms of aberration compensation where the complete elimination of aberrations is not attainable. The mathematical treatment throughout reaches a standard of clarity and rigour somewhat rare in optical work.

At the risk of appearing ungracious to an author whose book should prove of conspicuous service we would refer to two almost trivial inaccuracies that have been noticed. Dr Herzberger has departed from the recent practice of the Jena school of opticians, who have admitted the claims of Robert Smith as the discoverer of the elementary form of the sine relation, and specifically claims original authorship for Lagrange, who wrote sixty-five years later. It is only fair to add that some English writers persistently make the same mistake. The other error is in the index, where all page numbers referring to the bibliography are too great by 2. Incidentally the bibliography refers to many publications which are not mentioned in the text of the book.

This book occupies at present a unique position. It is the only publication which brings together and builds into a single structure many of the outstanding advances made in this century by writers of different nationalities. As an introduction to the modern aspects of geometrical optics it therefore stands alone, and no one who desires to learn what has been achieved in the past thirty years and so be helped to follow the work now being carried out should fail to read it.

T. S.